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Recycling of plastics in Germany

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Abstract

This article deals with the waste management of post-consumer plastics in Germany and its potential to save fossil fuels and reduce CO_2 emissions. Since most of the experience available is for packaging the paper first gives an outline of the legislative background and the material flows for this sector. The recycling and recovery processes for plastics waste from all sectors are then assessed in terms of their potential contribution to energy saving and CO_2 abatement. Practically all the options studied show better performance regarding these two aspects than waste treatment in an average incinerator (which has been chosen as the reference case). High ecological benefits can be achieved by mechanical recycling if virgin polymers are substituted. The cost effectiveness of reducing energy use and CO_2 emissions is determined for a number of technologies. There is large scope to reduce the costs, with an estimated overall saving potential of 50% within one to two decades. The paper then presents scenario projections which are based on the assumption that the total plastics waste in Germany in 1995 is treated in processes which will be available by 2005; considerable savings can be made by moving away from the business-as-usual path to highly efficient waste incinerators (advanced waste-to-energy facilities). Under these conditions the distribution of plastics waste among mechanical recycling and feedstock recycling has a comparatively small impact on the overall results. The maximum savings amount to 74 PJ of energy, i.e. 9% of the chemical sector's energy demand in 1995 and 7.0 Mt CO_2, representing 13% of the sector's emissions and 0.8% of Germany's total CO_2 emissions. This shows that plastics waste management offers some scope for reducing environmental burdens. The assessment

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[1] 1 Mt = 1 metric megatonne = 10^9 kg = 2.205*10^9 lb; 1 PJ = 1 petajoule = 277.8 GWh.

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does not support a general recommendation of energy recovery, mainly due to the large difference between the German average and the best available waste-to-energy facilities. [1]

Keywords: Plastics; Recycling; Waste-to-energy; Energy saving; CO_2 abatement; Costs

1. Introduction

Since the early 1990s, a considerable effort has been made to recycle plastics in Germany. This is one element of the German Federal Government's long-term policy to integrate the concept of sustainable development in various fields of the economy. As a result, today Germany is the largest market for recycled plastics in Europe, followed by Spain [1]. Much progress has been achieved in the recycling of *pre*-consumer plastics waste where there is little scope for further optimisation [2]. But the share of recycled *post*-consumer plastics waste is estimated at only 20–25% (see below, Table 1). Moreover, the amount of *post*-consumer plastics waste exceeds the amount of pre-consumer waste by a factor of 3.5–5 (depending on the information sources and the year of analysis), and this ratio will increase considerably in the future due to waste from long-term applications, the share of which will rise in the next few years. For these reasons, this article focuses on the recycling of post-consumer plastics waste.

Most of the experience available is on post-consumer waste from the packaging sector. In Germany, the collection and sorting of packaging materials is organised by the *Duales System Deutschland* (DS, former token DSD) which carries a green dot as its trademark. The *Deutsche Gesellschaft fuer Kunststoff-Recycling* (DKR) is responsible for plastics recycling within the DS framework. Organisations which are similar to DS are gaining ground in other Western European countries [3], and an equivalent could also be introduced in Japan in the near future.

There are several reasons why DS was introduced in Germany as the outcome of negotiations between industry and government:

- Packaging constitutes a considerable share of municipal solid waste (30% by weight and 50% by volume; [4]) and landfill capacity (which is still the main disposal method used in Germany) was declining rapidly.
- Environmental considerations, geological limitations, land use aspects and public pressure imposed constraints on the expansion of landfill capacity.
- From the year 2005 onwards, municipal waste will have to be incinerated and only landfilling of the residues will be allowed according to a federal ordinance (*TA Siedlungsabfall*). Given the public resistance to new incineration plants and the conspicuousness of plastics waste, the decision was made to implement a recycling scheme for packaging.
- The legislative backbone of DS is the Packaging Ordinance (*Verpackungsverordnung*) and the Recycling Management and Waste Act (*Kreislaufwirtschafts- und Abfallgesetz*). At the European level there is a Packaging Directive which was passed in December 1994. National ordinances, European documents and volun-

tary agreements have also been passed or are being discussed in other fields of plastics use, i.e. for end-of-life vehicles and electric and electronic waste [5].

Waste management for plastics is within the focus of public attention and it forms an important part of environmental policy. It should be designed such that it contributes to the government goals to decrease CO_2 emissions by 25% between 1990 and 2005, to increase resource productivity[2] by a factor of 2.5 between 1993 and 2020 and to increase waste use by 15% up to 2010 [6].

The scope of this paper is the recycling of post-consumer plastics that originate from all fields of application; however, if there is specific experience available from the packaging sector, it is presented, and an effort is made to translate the findings to plastics recycling in general. First of all, this paper presents an overview of the material flows in plastics recycling from the packaging sector. Secondly, environmental comparisons are made for recycling processes, for waste from both packaging and non-packaging applications. The ecological indicators chosen are gross energy requirements[3] and the gross CO_2 emissions. One section deals with the recycling costs for plastics packaging since this is the only area in which indications on present and future costs are available. Other sections deal with the potential application of recycling by groups of technologies, as well as estimates of the savings of energy and CO_2 at the macrolevel. The paper closes with a discussion of the results and several conclusions.

2. Material flows in packaging recycling

DS is responsible for the management of all packaging materials from the private sector and small consumers, i.e. for plastics, glass, paper/cardboard, tin, aluminium and composites. Plastics packaging handled by DS amounts to about 800 kt which is equivalent to $\approx 60\%$ of all plastics packaging materials [7] and about 11% of the total consumption of plastics products (see Table 1). On the waste side, DS covers 20–25% of total plastics waste and accounts for about 70% of the total recycling of post-consumer plastics in the country (Table 1). This shows the success of DS since its introduction in 1990. It is also evident that the goal of realising a comprehensive recycling system for plastics from all sources will still require a great effort.

DS does not cover sales packaging from large industries, auxiliary and transportation packaging. No mandatory quotas have been fixed for such packaging materials, nor is there an obligation to report. However, they must be re-used or recycled as far as this is technically feasible and economically sound (Recycling

[2] Defined as Gross Domestic Product in prices of 1991 over the consumption of non-renewable resources, e.g. fuels, rock, stone and mineral products.

[3] Gross energy requirements (also referred to as 'Cumulative energy demand') is defined as the energy consumption in terms of primary energy for the entire system, starting with the extraction of resources from the various deposits and ending with the product(s) under consideration. Gross CO_2 emissions are defined by analogy.

Management and Waste Act, *Kreislaufwirtschafts- und Abfallgesetz*, §4 (2) and §5 (3)).

Since the enactment of the Packaging Ordinance and the subsequent establishment of DS in 1991, the consumption of packaging materials has declined by 12% and for plastics packaging by 4% (by weight; [7]). The relatively small reduction in plastics packaging is because plastics have continued to replace other packaging materials. Without new plastics packaging designs — using less material for the same function [8] — this decrease would have been even less. Obviously these developments are most welcome since the avoidance of material input (and waste) without any losses in terms of functionality is economically and ecologically the most efficient option. However, according to some analysts this development of dematerialization was hardly promoted by virtue of new legislation or by DS, i.e. it is regarded as an autonomous development which is triggered by economics and technological progress [9]. On the other hand, since DS fees are up to 2.5 times as high as the price of virgin polymers, it would seem unlikely that DS has no influence on the demand for plastics. It is apparently impossible to quantify the contribution of the various drivers. In any case, the changes DS has induced on the side of waste management (i.e. the setting up of sorting facilities, recycling plants, etc.) are by far more obvious than the small reductions in the consumption of

Table 1
Consumption, waste generation and recycling of all plastics products and of DS plastics packaging in Germany, 1996 [38,48,10][a]

	kt
All plastic products	
Consumption	~7450[b]
Post-consumer waste	
According to ISI	3650[b]
According to Sofres	3147
Recycling	756
Feedstock	258
Mechanical	498[c]
DS packaging[d]	
Consumption	792
Collected post-consumer waste	~780[e]
Recycling	535
Feedstock	258
Mechanical	277

[a] All values refer to the year 1996 and are given in metric kilotonnes (kt).
[b] Own estimate, based on [38]. Excluding chemical fibres and non-plastics.
[c] Share of mechanical recycling over total post-consumer waste: 14% (basis, ISI) to 16% (basis, Sofres).
[d] 'DS packaging' is a subgroup of 'All plastic products' (see upper section of table).
[e] See footnote c in Table 2.

plastics packaging. This directs attention to waste management and its economical and ecological impact, subjects that will be discussed in the following.

The data for DS plastics packaging given in Table 1 are broken down further in Table 2; the figures for 1997 in Table 2 show that the total amount of DS plastics packaging waste equalled 820 kt and that the valuable output from the sorting facilities was 567 kt, i.e. 69%[4]. The remaining 31% represents the amount of refuse from sorting facilities that ended up in incineration plants or landfills. In 1997 a total of 615 kt was recycled. This is more than the output from the sorting facilities (567 kt), the difference being due to the change of stocks. To make a comparison with the mandatory quota easier (see column on right hand side) the change of stocks has not been taken into account in Table 2, i.e. all the data listed refer to a total of 567 kt (amount of sorted plastics waste). Fifty-eight per cent (331 kt) of the sorted plastics waste was fed to feedstock recycling facilities where the polymers are broken down to upstream products such as methanol and substitutes for fuel oil or crude oil. The remaining 42% was converted by mechanical recycling where the polymer remains intact and is reprocessed. The figure given for mechanical recycling comprises the amounts exported in the form of agglomerates and regranulates representing about 9%[5], whereas the remaining 33% was used domestically. The mandatory quota listed in Table 2 will be valid from 1 January 1999 onwards according to the new amendment of the packaging ordinance. If the mandatory quota and the real figures given in Table 2 were compared directly, i.e. without corrections to account for the change in definition of the reference quantity[6] and the change of stocks (see above), the conclusion would be drawn that the share of mechanical recycling will have to be increased (target value, 36%) in order to comply with the new legal framework, whereas the percentage for sorted waste was already over-fulfilled in 1997. However, as a consequence of the new amendment, the reference quantity has declined from 822 kt in 1997 to 517 kt in 1998 (licensed amount of packaging [10]). For this reason all quotas have been overfulfilled in 1998 [10].

The achievements in Germany can also be compared to the requirements of the European Packaging Directive which stipulates that a minimum of only 15% of each packaging material (e.g. plastics) must be recycled. Based on the total plastics packaging waste (including packaging without the green dot) this quota represents no more than 250 kt, i.e. DS went beyond the requirements for all plastics packaging by a factor of two in 1997.

Table 2 also shows a distinction between products made by mechanical recycling, which is also referred to as Back-to-Polymer recycling or BTP recycling. Virgin

[4] This definition is not identical with the one chosen in the German DS monitoring system (see footnote c in Table 2).

[5] Five percent of which were exported to European Union countries and the remaining 4% to other countries [11].

[6] See footnote c in Table 2.

Table 2
Recycling of plastics packaging by DS in 1996 and 1997 [11,33][a]

	1996			1997			Mandatory quota from Jan. 1st, 1999
	kt	% (780 kt = 100%)	%	kt	% (820 kt = 100%)	%	%
Collected plastic waste[b]	780[c]	100		820[c]	100		100
Sorted plastic waste	535	69	100	567[d]	69	100	60
Feedstock recycling	258	33	48	331	40	58	
Mechanical recycling, domestic	71	22	32	185	23	33	
Mechanical recycling, abroad	106	14	20	51	6	9	
Incineration	0	0	0	0	0	0	
Mechanical recycling by waste fractions	277	36	100	236	29	100	36[f]
Films	144	19	52	153	19	65	
Bottles (mainly PE, PP)	48	6	17	51	6	22	
Cups, beakers (mainly PS, EPS)	16	2	6	11	1	5	
Mixed plastics	68	9	25	21	3	9	
Mechanical recycling by quality of products[e]	277	36	100	n.a.	n.a.	n.a.	
BTP Polymer substitutes	224	29	81	n.a.	n.a.	n.a.	

Table 2 (Continued)

	1996			1997			Mandatory quota from Jan. 1st, 1999
	kt	% (780 kt = 100%)	%	kt	% (820 kt = 100%)	%	%
BTP Non-polymer substitutes	53	7	19	n.a.	n.a.	n.a.	
For domestic use	45	6	16	n.a.	n.a.	n.a.	
Exported	8	1	3	n.a.	n.a.	n.a.	

[a] 1 kt = 1 metric kilotonne = 10^6 kg = 2.205×10^6 lb.

[b] Includes only plastics packaging collected by DS; other materials/products are excluded.

[c] Own estimate of plastics packaging in the ‘yellow sack’ (based on the collection/recovery ratio in 1995). The entries are close to the DS figures on packaging consumption in 1996 (792 kt) and 1997 (822 kt) which have been used as the reference quantity in the German Packaging Ordinance (by contrast, the licensed amount of packaging has been chosen as the reference quantity in the amendment passed by the Bundestag on August 28th 1998). The difference between the figures for collected plastics waste (820 kt in 1997) and sorted plastics waste (567 kt in 1997) gives the refuse rate from sorting units which is incinerated or landfilled.

[d] In 1997 a total of 615 kt was recycled. This is more then the output from the sorting facilities (567 kt) the difference being due to the change of stocks. To make the comparison with the mandatory quota easier (see column on right hand side) the change of stocks has not been taken into account in this table.

[e] BTP stands for back-to-polymer recycling, i.e. for mechanical recycling. The percentages for mechanical recycling by quality of products have been taken from [33]. The quantities in absolute terms (in kt) have been calculated on this basis. Even though the distinction between ‘BTP polymer substitutes’ and ‘BTP non-polymer substitutes’ is bound to be relative depending on the standards chosen, the percentages give an initial indication of the distribution.

[f] The definition of the reference quantity chosen in the German Packaging Ordinance differs from the definition of ‘collected plastic waste’ chosen in this table. However, the values are very close (see footnote c), so it is possible to compare the mandatory quota given in the last column with the achieved percentages listed in the preceding columns.

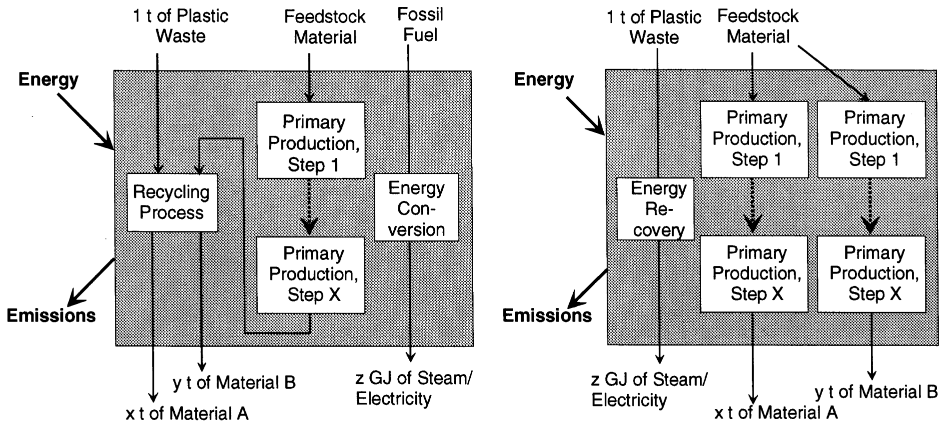

Fig. 1. Method applied for the ecological evaluation of a recycling process with waste incineration as reference case.

polymers are replaced in the case of 'BTP polymer substitutes' products. 'BTP non-polymer substitutes', on the other hand, represent goods which are usually manufactured from wood, concrete or iron and steel. Most of these are produced from mixed plastics waste.

3. Environmental comparison of processes

Different processes result in different products and, therefore, the benefits also vary from technology to technology [12]. Whilst this understanding is fully acknowledged in economic comparisons it is less so for ecological analyses. To take this aspect fully into account the methodology presented in Fig. 1 will be used for the environmental assessment: the left part of Fig. 1 shows that the recycling of one tonne of plastics waste results in a number of valuable outputs (materials), and that its operation is accompanied by energy requirements and the release of emissions. On the other hand, the same amount of plastics waste (1 tonne) can be combusted in an average municipal waste incinerator (this includes the whole range of plants, from simple incinerators to advanced waste-to-energy facilities); this results in the output of steam and electricity (reference case, see right side of Fig. 1; definition of 'average' is given below, see text). So far the two systems are not comparable since they both lead to a different vector of products. To ensure comparability, each of the two systems is complemented by the respective flows (materials and secondary energies). It is assumed that these are produced in the conventional way, i.e. from fossil resources, which is also referred to as virgin production or primary production. Primary production also requires energy inputs (usually both as process

Table 3
Gross energy requirements and gross CO_2 emissions for primary production of feedstocks, secondary energies, intermediates and materials [49][a]

	Reference	Gross energy requirements (kg/reference)	Gross CO_2 emissions (kg/reference)
Feedstocks and secondary energies			
Crude oil	1 t	43.3	34
Fuel oil	1 t	46.4	180
Naphtha	1 t	47.2	180
Steam (losses included)	1 GJ	1.4	98
Electricity	1 GJ	3.1	186
Intermediates			
Benzene, Toluene, Xylene	1 t	54.3	770
Methanol (feedstock mix Germany)	1 t	40.2	1400
Methanol (from natural gas[b])	1 t	36.1	930
Ethylene	1 t	61.3	770
Propylene	1 t	59.9	770
Styrene	1 t	66.7	1570
Materials/products			
Polymers			
PA6	1 t	122.7	6130
PE[c]	1 t	64.6	1240
PET	1 t	59.4	2070
PMMA	1 t	77.7	3580
PS	1 t	70.8	1870
PUR	1 t	78.0	3050
PVC	1 t	53.2	2080
Wood			
Pallets	1 t	9.1	555
Fences, benches	1 t	41.0	2540
Concrete			
Fence holders	1 t	4.0	270
Sewers, noise protection	1 t	1.6	110

[a] Gross energy requirements include both process and feedstock energy. Gross energy requirements and gross CO_2 emissions refer to the system 'cradle-to-factory gate'.

[b] The production of methanol from natural gas is only listed to provide a comparison with the production from the feedstock mix used in Germany. Throughout this study the German feedstock mix was assumed for primary production.

[c] PE has been assumed as the virgin substitute for recyclates made of mixed plastics.

energy and as feedstock) and leads to emissions. The assumed gross energy requirements and gross CO_2 emissions are listed in Table 3.[7,8]

Using this so-called product basket-method the net effect of recycling is determined by calculating the difference between the values for each ecological indicator of the two systems. It is possible that the net effect of recycling is advantageous for one ecological indicator, and negative for the other. The ecological indicators analysed in this paper are gross energy requirements and gross CO_2 emissions. The calculation procedure is repeated for each recycling technology and finally the net effects are compared and assessed.

As mentioned, the incineration of plastics waste in an average plant is used as the reference case on the waste management side. Other studies choose landfilling as the reference case [13]. Both approaches are possible. In principle the results can easily be transformed into each other.[9] The choice made in this analysis originates from the fact that direct landfilling of plastics will be prohibited from the year 2005 onwards (*TA Siedlungsabfall*). In this context it must be mentioned that the technical standards of German municipal waste incineration plants vary greatly. An inventory of the existing facilities in Germany including the net efficiencies for the generation of electricity and district heat is not available, so the data of an average plant had to be estimated: According to a random sample, one Gigajoule of waste (lower heating value, LHV) substitutes about 0.55 Gigajoules of primary energy required to produce the same amount of electricity and/or heat in power stations and district heating plants.[10]

The recycling technologies analysed include mechanical recycling and various types of feedstock recycling. Energy recovery technologies are also assessed, i.e. the combustion of plastics in cement kilns and in advanced waste-to-energy facilities. The Mannheim facility in Germany was used for the latter.[11]

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[7] When looked at in more detail, the calculation method is more complicated than shown in Fig. 1. For example, sorting is required prior to recycling. In this study it is assumed that sorting residues are incinerated, resulting in outputs of steam and electricity. To ensure comparability, the reference case must be complemented accordingly.

[8] Own estimates for the energy demand and for CO_2 emissions resulting from the logistics (collection, sorting, transport) lead to the conclusion that the burdens are more or less invariant across the alternative waste inputs or collection systems. This does not apply to the treatment in municipal waste incineration and landfilling, mainly due to the omission of sorting and washing processes. In contrast, all recycling processes have been charged with the average burden (energy and CO_2) of the logistics of DS plastics waste. This is a safe assumption since DS plastics waste is rather commingled, consists of many small pieces and requires washing. Thus, the burden for logistics related to other plastics waste streams and other plastics recycling processes tends to be smaller in reality.

[9] But further differences in assumptions, e.g. concerning the treatment of sorting residues (incineration vs. landfilling, see footnote 7) and different reference quantities (plastics waste at the source vs. plastics waste after sorting), make it rather difficult to transform the results of different studies into each other. This is also the reason why there is only limited comparability between the results of this study and those generated by Fraunhofer IVV [13].

[10] For example, in one case the net electricity generation and the utilized heat output both amounted to about 12% (final energy over LHV of waste input).

[11] The net electricity generation in the Mannheim waste-to-energy facility in Germany is about 8%, and the utilized heat output is about 64% of the LHV of the waste input [14].

In the case of mechanical recycling three categories can be distinguished:

- The first covers those products which are usually manufactured from virgin polymers. Here, a distinction can be made between recycled products which serve the same purpose (e.g. from bottle to bottle) and those which fall into a different category of application (e.g. from bottle to fibre). It must be taken into account that blending or compounding may be necessary, i.e. that a certain amount of virgin material is also required in the recycling process. For other products it may be necessary to use more recyclates than virgin plastics to achieve the required mechanical properties. In both cases, the substitution factor is $< 100\%$. The smaller the substitution factor, the smaller the ecological advantage compared to virgin production.
- Second, there are goods which, in conventional production processes, are not made from plastics, e.g. fences, crates, pallets, garbage bins, sheets used in trucks and in the building sector, or polyurethane particles used as an oil sorbfacient (instead of sand in the case of oil spills). Within this category, the ratio of lifetimes and the ratio of in-use efficiencies are important parameters to be taken into account. Aspects which cannot be quantified in terms of the indicators analysed in this paper are the differences between conventional and recycled products concerning product properties, processability, transportability, etc.
- Third, recyclates can be used to provide totally new products or services, e.g. artificial snow ([15], p. 228). It is very difficult to conduct an environmental assessment for this category since a change of lifestyle, for instance, may be involved and this creates problems when defining primary production. Therefore, this last option will not be taken into account in this assessment.

Fig. 2 shows the savings of gross energy and gross CO_2 emissions for the various processes. Some of the processes have already been proven on a large scale whereas others are still in the development stage. Practically all options show a better environmental performance compared to plastics waste treatment in an average municipal waste incinerator (reference case).

There is a great difference between advanced waste-to-energy facilities and the average of all incineration plants. The Back-to-Feedstock recycling technologies (BTF) included in the solid bar comprise the blast furnace process and hydrogenation. These BTF recycling technologies are clearly preferable to an average incinerator, but the resulting savings of gross energy are only about two thirds of those of an advanced waste-to-energy facility. Recycling back to monomers (BTM) is a very attractive proposition for some engineering plastics (see footnote in Fig. 2), but the collectable volumes of the respective waste streams are relatively small. Mechanical recycling (BTP) resulting in 'non-polymer substitutes' shows a particularly wide range of values since the environmental impact of primary production differs greatly depending on the material substituted and the subsequent finishing process. Moreover, it is not always clear what to assume for primary production and consequently the results are somewhat uncertain. The evaluations are also liable to become outdated quickly since many of these products are also good candidates for other recycled materials, e.g. recycled cardboard [16]. Finally, mechanical recycling

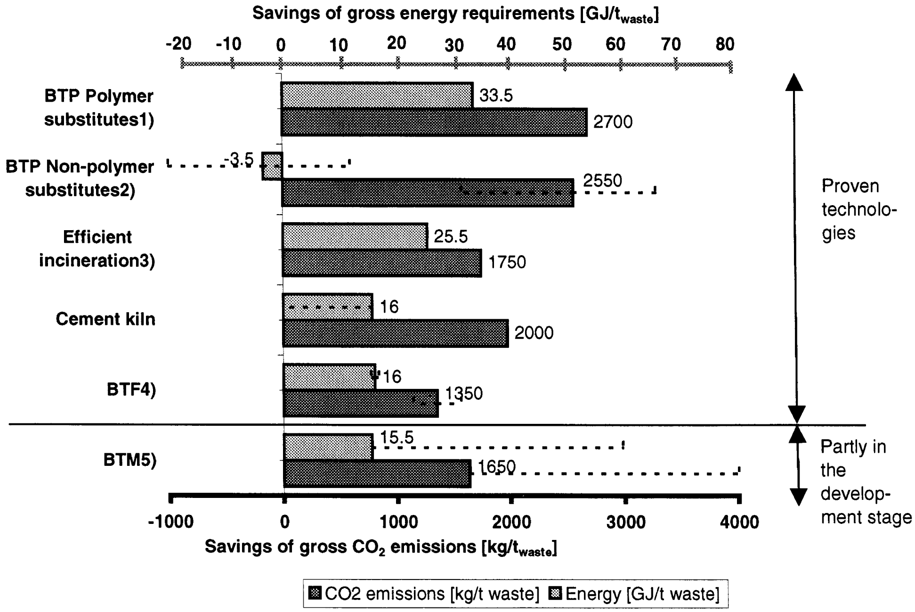

Fig. 2. Savings of gross energy and gross CO_2 emissions due to recycling and recovery processes for post-consumer plastics (reference case; average of all municipal waste incinerators). (1) Figures represent the weighted average of various types of mechanical recycling.[D)] Individual datasets are (substitution factor = 1.0): PVC (22 GJ/t, 3050 kg CO_2/t), PE (35 GJ/t, 2250 kg CO_2/t), PS[D)] (41 GJ/t, 2900 kg CO_2/t), PUR (53 GJ/t, 4350 kg CO_2/t), PMMA (50 GJ/t, 4650 kg CO_2/t). For comparison, with a substitution factor of 1.2: PE (25 GJ/t, 2050 kg CO_2/t), PS[D)] (29 GJ/t, 2500 kg CO_2/t). (2) These processes are characterized by a extraordinarily wide range of data depending on the primary production process. (3) There are only very few municipal waste incineration plants of this efficiency in Germany. (4) Comprises the blast furnace process[D)] and hydrogenation[D)]. For gastification and subsequent methanol production (SVZ)[D)] the figures are 3 GJ/t and 50 kg CO_2/t. (5) The solid bars give the values for the Hamburg pyrolysis of PE. Much higher savings are feasible for other polymers (dashed line), e.g. for PS (36 GJ/t; 2500 kg CO_2/t), PMMA (48 GJ/t; 4500 kg CO_2/t), PA6 (63 GJ/t; 5450 kg CO_2/t). (D) These processes are currently used within DS.

(BTP) leading to 'polymer substitutes' shows the highest ecological advantages, with the exception of BTM recycling for certain types of plastics (see above). Mechanical recycling substituting virgin polymers is a feasible option, particularly if a waste stream can be used which contains only one type of polymer.

Energy recovery in cement kilns enables CO_2 savings which are slightly higher than those that can be achieved in an advanced waste-to-energy facility, but cement kilns contribute far less to energy conservation. There are some difficulties related to the assessment of cement kilns which will be discussed later on (Section 6).

4. Recycling costs for plastics packaging

Since empirical cost data are currently only available for the DS, the following analysis of the economics of recycling and energy recovery is restricted to plastics packaging waste from private households and small consumers. It is understandable

Table 4
Material flows of DS packaging materials and their costs in 1996 [17,10]

Type of packaging material and waste management step	DS waste management costs in 10^9 DM[b]	Consumption of packaging material, in kt[a]	Specific costs, in DM[b] per ton of packaging material consumed	Sorted packaging waste[c], in kt	Specific costs, in DM[b] per ton of sorted packaging waste
All packaging materials[d]	3.855	6323	610	5323	720
Plastics packaging	1.799	792	2270	535	3360
Logistics and sorting	1.284		1620		2400
Processes	0.515		650		960

[a] The amounts given in this column represent the quantities DS holds liability for.
[b] 1 Deutsch Mark (DM) is equivalent to about EURO 0.524 and US$ 0.665 (1996).
[c] The amount of sorted packaging waste is equivalent to the quantity that is recycled and recovered.
[d] Including plastics, glass, paper/cardboard, tin, aluminium and composites.

that plastics, being the newcomers in the recycling business, currently entail the largest specific costs (Table 4).

In 1996, the overall specific system costs from the packaging sector amounted to DM 3360 per tonne of sorted plastics waste (see Table 4) [17]. Given these high figures relative to the prices of virgin polymers and other materials it is obvious why DS has declared cost reduction as one of the major goals in the near future[12] [11,18–21]. Fig. 3 shows the expected short-term potentials for cost saving which are mainly based on a report prepared by the Bavarian Institute for Waste Research (BIfA) [17]. Due to the time required to recoup the invested capital and for the diffusion of cost-saving measures, only a part of the saving potential as presented in Fig. 3 for 1998 and 2000 can become effective immediately. The data shown rather reflect possible cost reductions for new investments beyond the year 2000.

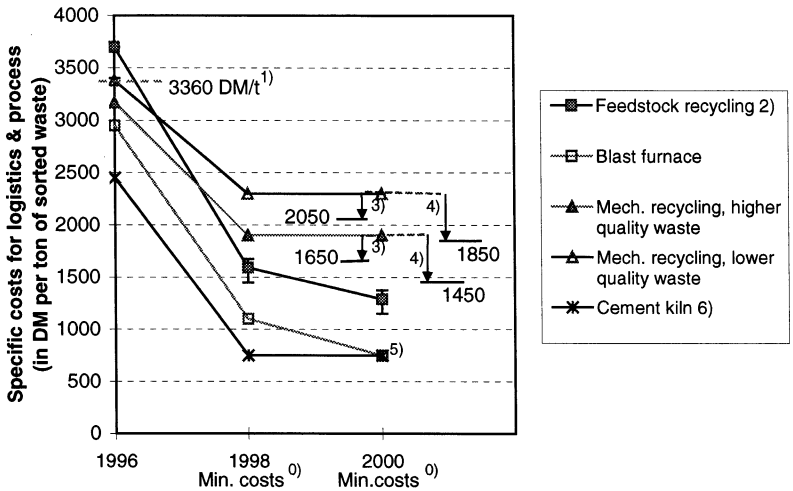

Fig. 3. System costs for waste management of DS plastics in 1996 and estimation of maximum theoretical cost savings in 1998 and 2000 (various sources, see text). (o) Potential minimal costs for new investments in 1998 and 2000, respectively, not average of all plants. (1) Weighted average over all waste plastic treatment processes licensed by DS in 1996. (2) Weighted average over all feedstock recycling technologies licensed by DS in 1996, i.e. hydrogenation (65 kt), and gastification (70 kt). Blast furnaces are presented separately. The ranges give the variation of costs for hydrogenation, gastification and pyrolysis. (3) Requires the introduction of an additional bin for small and dirty pieces of plastic packaging waste. (4) Requires the introduction of bring systems for larger plastic packaging items to be recycled mechanically. (5) Total costs (logistics and process) for blast furnace and cement kilns in the year 2005: 700 DM costs for collection and segregation are included. (6) DS costs for collection and segregation are included.

[12] The costs incurred for collecting, sorting and recycling of plastics packaging are financed by way of a fee DS charges to companies that use packaging materials. The DKR (the organisation in charge of plastics recycling within DS) has announced that it will reduce these fees and thus reduce the organisation's total costs.

In feedstock recycling, most of the development and implementation expenses have already been reimbursed to the recyclers and this will result in a decline of contracted costs in the years to come. For example, process subsidies (without agglomeration) for blast furnaces, which amounted to ≈ 250 DM per tonne of sorted plastics waste in 1996, were lowered to 100 DM/t in 1998 and will be phased out by the end of the year 2003 [20]. From the year 2000 onwards the automation of sorting technologies will further reduce the costs, feedstock recycling being the main beneficiary according to current information (a saving of 300 DM/t) [17]. In Fig. 3 it is assumed that expenses for automated sorting will amount to 500 DM/t by the year 2000 [17] but the increased diffusion of this technology, as well as novel designs (e.g. using infrared spectroscopy), may push costs down to around 300 DM/t. Moreover, experience in Bavaria shows that both the economics and the quality of waste can be improved if bring systems are installed [17]. Similar effects are expected from the introduction of an additional bin which again demonstrates the cost impact of the system's design and the consumers' cooperation. The last two measures (see the vertical arrows in Fig. 3) will no longer be considered since it is assumed that the logistics (i.e. collection) and the subsequent separation and pre-treatment processes will remain unchanged in the medium term.

The cost projections presented so far relied on assumptions concerning technological improvements. For purposes of comparison, the knowledge of microeconomics and their experience curves can be applied [22,23]: there is strong empirical evidence that the cost reduction potential amounts to 10–15% for each doubling of the cumulative amounts (here; of recycled plastics), given the fact that the type of machinery and processes are similar to what has been observed in the past [24–26]. Assuming that the observations made with experience curves are transferable to the processes analysed in this paper, recycling costs may fall to 50% between 2005 (assuming a 15% decrease by doubling of cumulative recycled material) and 2020 (assuming a 10% decrease). These calculations assume an increase in plastics recycling by 15% p.a. up to 2005, a reduced growth of 7.5% for the period 2005–2010 and stagnation from 2010 onwards.[13]

To summarise, the cost projections made on the basis of technological analysis (Fig. 3) and experience cost curves indicate that it is possible to reduce the costs in the medium term by half, i.e. within one to two decades (considering the time requirements for diffusion and assuming the same shares of the various recycling processes as in 1996). Similar cost reduction potentials have been claimed by the proponents of other waste management concepts.[14] This confirms that there is still much scope for economic optimisation with current waste plastics management systems. This is also supported by DS's short-term goal to cut their total costs (for all packaging materials) by 700×10^6 DM or 17% up to the year 2006 [19].

[13] This includes plastics waste from non-packaging applications. It is appropriate to include waste from these sources since, to a large extent, the same technologies are used to recycle plastics waste from packaging and non-packaging.

[14] E.g. a certain type of refuse-derived fuel called *Trockenstabilat*, the literal translation of which is dry stabilate ([9] p. 81).

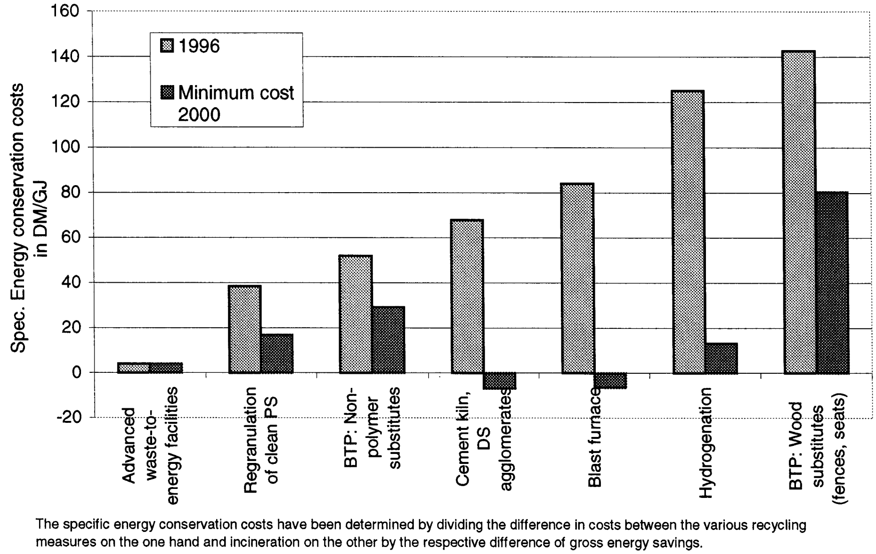

Fig. 4. Specific energy conservation costs of plastics recycling/recovery in Germany (for selected technical options; reference case; average of all German municipal waste incinerators).

The cost reduction potential may still be underestimated by the two methods applied because further savings seem to be achievable by changing the boundary conditions. For example: the legal obligation to co-ordinate the activities with the local MSW authorities (*Abstimmungspflicht*) can currently lead to a costly combination of different systems [9,17]; this could be an interim phenomenon. Moreover, German anti-trust jurisdiction calls for separate bodies for the management of waste from sales packaging originating from private households and small consumers on the one hand, and from industry on the other hand, as well as for transport packaging [9]. These legal boundary conditions may change in the future. It goes without saying that the economics of plastics recycling also depend on future oil prices [27] and taxation schemes, due to their impact on virgin product prices which, in turn, determine the price of recyclates.

Waste treatment serves several purposes, e.g. hygiene, ecological considerations and aesthetics. It is therefore inappropriate to ascribe the *total* costs of plastics recycling (as given in Fig. 3) to the two ecological indicators analysed in this paper (conservation of fossil resources and CO_2 abatement). By analogy with the method adopted for environmental comparisons an average waste incinerator in Germany has been chosen as the reference case[15]. Consequently, the costs devoted to savings of fossil fuels and CO_2 emissions are defined as the difference in the cost of the various recycling measures on the one hand and incineration on the other. Dividing this cost difference by energy and CO_2 savings respectively leads to the values given

[15] Assumed average costs for waste incineration plants including collection and transport: 625 DM per metric tonne; no economic credit has been assigned to plastics waste to account for its energy content.

in Figs. 4 and 5. In all cases, cost effectiveness can be improved decisively in the next one to two decades (see 'minimum cost' projections representing the specific costs of new facilities built in 2000). Since the specific energy conservation and CO_2 abatement costs have been determined in relation to average waste incineration in Germany they may become negative and thus represent a macroeconomic benefit. This is the case for cement kilns and blast furnaces if the cost saving potential available by the year 2000 is fully exploited (Figs. 4 and 5).

Figs. 4 and 5 do not take into account that plastics waste represents a resource of limited availability and that the amount of plastics waste required to save 1 GJ of energy or 1 t of CO_2 (Fig. 2) can differ from process to process. Therefore, a strategy which is optimised in techno-economic terms has to take into account both the indicators shown in Fig. 2 and those in Figs. 4 and 5.

In order to avoid misinterpretation of the cost data shown in Figs. 3–5 it has to be stressed that they represent *system* costs, not *technology* costs. System costs include the recyclers' profits which, in some cases, may have been substantial due to the high inherent risks of the related investments. In addition, system costs comprise considerable learning and development costs due to the innovative character of this industry and the target of establishing a large-scale system in an extremely short period of time (which also required comparatively high internal interest rates as an investment incentive). By contrast, technology costs represent the expenses from the engineer's point of view, and these often fail to cover transaction costs and other hidden costs. It is a well-known fact that the difference between system costs and technology costs can be substantial.

Interesting comparisons can be made by analysing the effects of energy and carbon taxes. The suggestions put forward in the European Union concerning

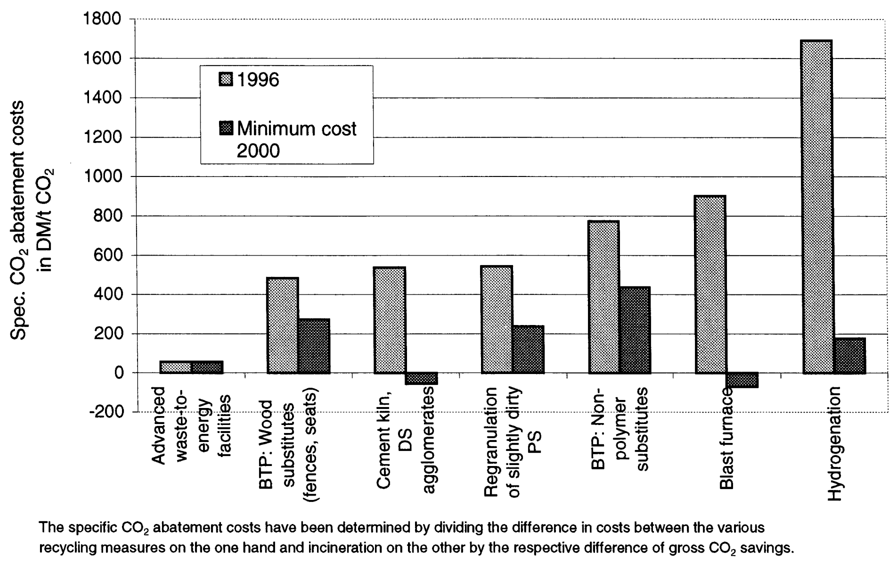

Fig. 5. Specific CO_2 abatement costs of plastics recycling/recovery in Germany (for selected technical options; reference case: average of all German municipal waste incinerators).

energy tax rates range from US$ 3 to 10 per barrel. The upper limit of US$ 10 per barrel corresponds to almost DM 3.0/GJ, which is equivalent to DM 40 per tonne of CO_2. The specific cost data presented in Fig. 5 show that a carbon tax of DM 40 per tonne of CO_2 will not substantially change the cost-effectiveness of the waste management technologies. Even the much higher carbon tax, as was introduced in Sweden (about DM 95/t CO_2), would only result in a change for the advanced waste-to-energy facilities. This demonstrates the necessity for achieving cost reductions by improving the logistics, processes and products in order to increase the societal benefits from recycling of plastics packaging in the longer term.

5. Macrolevel scenarios

This section deals with the scenarios for the effects of recycling and energy recovery on energy consumption and CO_2 emissions at the macrolevel. The first step is to assess the feasible penetration of the various options. Table 5 shows the estimates for Germany by the year 2005. In the baseline scenario (scenario A), an average rate of 22% over all application areas was determined for mechanical recycling. If mechanical recycling within DS is excluded, this is equivalent to 12% which, in turn, falls into the same range of rates given in other studies [28,29]. The 22% estimate is also very close to the figure which can be derived from a recent Austrian study (24%; [30]). Table 5 also shows the estimates for the waste flows to be processed by feedstock recycling and incineration. In scenario A, the *average* energy efficiency of today's municipal waste incinerators in Germany was assumed (see Section 3). Compared to the best available units, this average is quite inefficient. By contrast, advanced waste-to-energy facilities have been assumed for scenarios B and C (these are among the best in operation in Germany, compare Fig. 2). In addition, it is presumed that only half of the non-mechanically recycled plastics waste is incinerated, whereas the other half is fed to feedstock recycling facilities. In scenario C, larger amounts of plastics waste are recycled mechanically (36%), representing the upper technical potential by the year 2005 (own estimates based on various sources, e.g. [31,32]). It has not been investigated whether this rate of recycling would exceed the absorption capacity of the recyclate market.

In Table 5 the rates for mechanical recycling have a special importance for the definition of the scenarios. While there are several obstacles to mechanical recycling, there are also ways to overcome them to a certain extent. Examples of these obstacles to mechanical recycling due to the high entropy of the waste are: the low weight of many plastics items (e.g. 60% of plastics packagings weigh < 10 g; [33], p. 3), material savings due to down-gauging (e.g. films made from PE using the metallocene catalysts), and new product designs (e.g. inliners, pouches). Moreover, the contamination of post-consumer plastics, the poor miscibility of many types of plastics, and the deterioration of material properties due to additives and softeners cause problems. These difficulties are often aggravated in the second and all subsequent recycling cycles. Examples of barriers on the demand side are: limitations in the use of recyclates for food packaging (no direct contact with food) and

Table 5
Rates for recycling and energy recovery for post-consumer plastics waste in Germany by the year 2005 (in terms of weight)

Application	Sector's share of total plastics waste (%)	Percentage of total waste per recycling/recovery technology								
		Scenario A: low BTP recycling and average incineration			Scenario B: low BTP recycling and BTF and advanced waste-to-energy facilities			Scenario C: high BTP recycling and BTF and advanced waste-to-energy facilities		
		BTP (%)	BTF (%)	Incin. (%)	BTP (%)	BTF (%)	Incin. (%)	BTP (%)	BTF (%)	Incin. (%)
Automobiles and mech. Engineering	16	14	0	86	14	43	43	29	36	36
E&E equipment[a], precision eng.	10	6	0	94	6	47	47	34	33	33
Packaging	35	37	0	63	37	31	31	41	29	29
Building	13	11	0	89	11	45	45	40	30	30
Agriculture	7	40	0	60	40	30	30	49	26	26
Household	6	9	0	91	9	46	46	22	39	39
Furniture	5	13	0	87	13	44	44	21	40	40
Other	8	20	0	80	12	44	44	26	37	37
Average (weighted)	100	22[b]	0	78	22[b]	39	39	36[c]	32	32

[a] Electrical and electronic equipment.
[b] Of which: 12.5% polymer substitutes; 9.7% non-polymer substitutes.
[c] Of which: 22.1% polymer substitutes; 13.5% non-polymer substitutes.

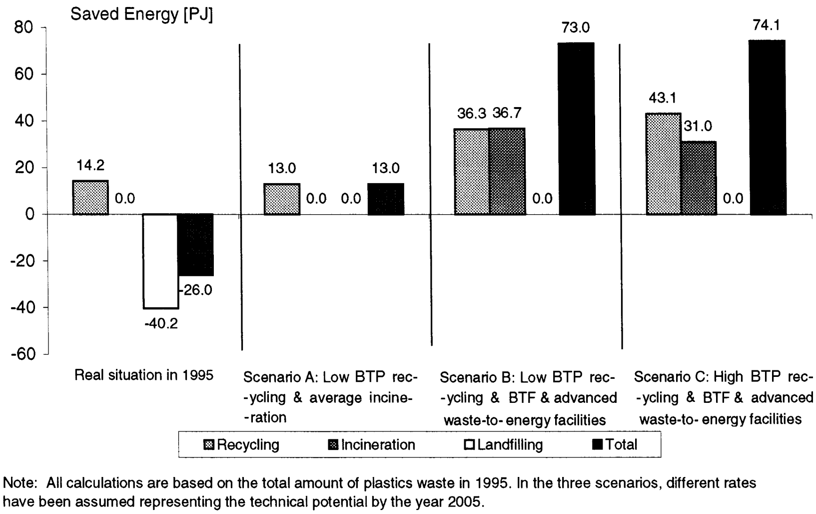

Fig. 6. The impact of recycling and energy recovery on gross energy requirements at the macrolevel — results for Germany, projected year: 2005 (reference case; average of all municipal waste incinerators in 1995).

over-specification in the standardisation of certain products [34], e.g. non-pressure pipes, garbage bins and cable ducts.

Examples of measures that improve the chances of mechanical recycling are: the automation of sorting technology, design for disassembly and recycling, and a trend towards single-resin systems observed in certain areas, e.g. in car interiors [35]. Further potentials are also available by co-extrusion [36], compatibilization [37], blending, the use of reinforcing agents and stabilisers and innovative technology for purification and processing.

The factors mentioned above determine the potential of mechanical recycling that differs from sector to sector (see Table 5). For example, the data for the automotive sector are based on the results of a project dealing with the techno-economic potential of disassembling plastics components [31]. In the case of electrical and electronic plastics waste one third is suitable for mechanical recycling according to a joint APME/VKE project [32].

By combining the results of the environmental assessment of recycling and energy recovery technologies with the rates described in the previous section, the contribution of a corresponding policy to energy saving and CO_2 abatement can be determined. All comparisons are based on the total amount of plastics waste in the year 1995[16] (3.65 Mt, without fibres [38]). The real situation in 1995 and three scenarios are shown in Figs. 6 and 7. Only the shares of landfilling, recycling and efficient incineration are varied and the aggregated results are compared. Landfilling, which was still available in 1995, prevents the emission of CO_2,[17] but energy is wasted (see the negative value in Fig. 6). Considerable savings could be made by the year 2005 by

[16] However, the fractions of waste arising from applications refer to the year 2005 (see Table 5, second column).

[17] CO_2 emissions are prevented in the short and medium term. However these may be released in the long term; in this case the environmental burden is simply shifted to the future.

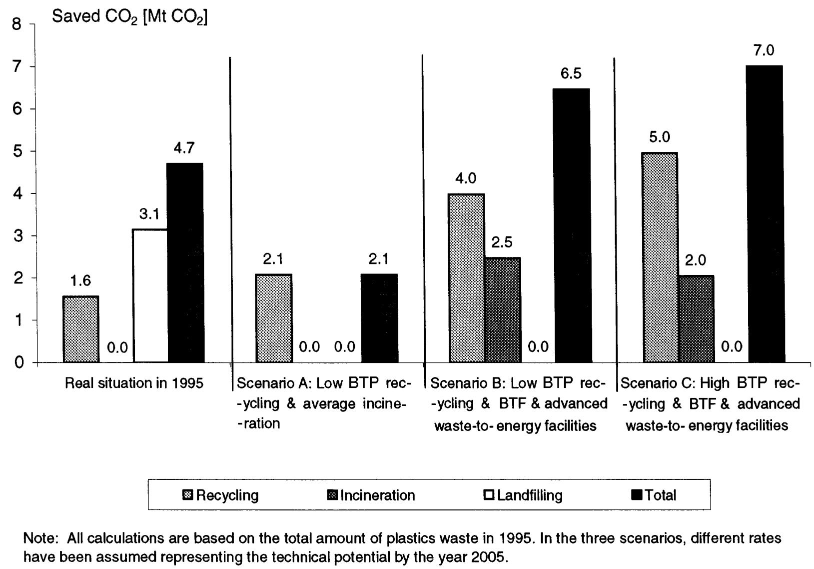

Fig. 7. The impact of recycling and energy recovery on gross CO_2 emissions at the macrolevel — results for Germany, projected year; 2005 (reference case: average of all municipal waste incinerators in 1995).

moving away from the business-as-usual path (scenario A) to a waste management system with advanced waste-to-energy facilities (scenarios B and C). Under this precondition an enhanced share of mechanical recycling increases the total gross CO_2 savings by about 8% (from 6.5 to 7.0 Mt) while the total gross energy savings remain practically constant (+1.5%, from 73.1 to 74.1 PJ).

To bring the data given in Figs. 6 and 7 into perspective, they can be compared with the gross energy requirements and gross CO_2 emission of the chemical sector (without non-energy use) which roughly equalled 800 PJ and 52 Mt CO_2 in 1995 (own calculations based on [39]). Hence in the two scenarios, B and C, an equivalent of about 9% of the chemical sector's energy demand and about 13% of its CO_2 emissions could be saved. The potential CO_2 savings identified are equal to 0.8% of Germany's total CO_2 emissions. The *real* environmental benefits achieved from improving the current recycling and recovery of post-consumer plastics will be even higher (also higher than stated in Figs. 6 and 7) since the amount of plastics waste will continue to rise in the future and the technologies for recycling and recovery will also be developed further.

6. Discussion and conclusions

In this paper, the gross energy requirements and gross CO_2 emissions have been chosen as indicators for the environmental impacts of various waste management strategies for plastics waste. Focusing on these two indicators is definitely a limitation, i.e. the inclusion of other types of impacts and other indicators, such as the savings of mineral resources, could lead to different findings. On the other hand, some authors argue that gross energy requirements represent a reliable sum parameter for an initial environmental comparison of process chains, if a full-size LCA cannot be conducted [40]. It would seem too audacious to argue that this also applies for all the recycling processes investigated in this paper. Differences in the release of emissions, apart from CO_2, and a possible contribution to savings of scarce resources (e.g. certain inorganic materials) could lead to different conclusions. Hence, the scope of this paper is very limited, the focus being on the contribution of plastics recycling to the goals of energy saving and CO_2 abatement.

One aspect which should be recalled at this point is the fact that the results of the environmental comparison and the cost-effectiveness analysis describe the advantages or disadvantages relative to today's standard primary production in Germany (manufacture of virgin materials) relative to an average incineration plant (reference case). This is considered to be the major source of uncertainty since, unfortunately, there is no inventory of German municipal waste incineration plants that includes their fuel mix, efficiencies and energy recovery data.

The comparability of processes is an aspect which is difficult to handle. To give the most important example: the heated discussions as to whether incineration in cement kilns can be considered as being comparable with the other processes from an environmental point of view. Cement kilns are not subject to the same air emission standards as municipal waste incinerators [41,42] and they generally use fuels with a high carbon content. Hence, using plastics as fuel in a cement plant will reduce CO_2 emissions more in comparison with other processes where low carbon fuels and feedstocks are already used (e.g. natural gas in the chemical industry). Moreover, the cost-effectiveness of burning plastics in a cement kiln might possibly be reduced if air emission controls have to be implemented to achieve similar standards as for incinerators. However it is argued that plastics may be cleaner than the coal they replace with regard to heavy metal contamination for instance [43].

While the problems of assessing the cement kiln process are very prominent, the evaluation of many of the other processes is also a matter of discretion. One example of this is given in Table 3 which contains the production of methanol from natural gas and from the feedstock mix used in Germany where a large share of heavy fuel oil is used. In this study the specifics of the production in Germany were taken as the reference (see also [44]). It should be kept in mind that the results can be influenced decisively by the regional boundaries and, moreover, by the chosen timeframe and the technological standard assumed. Therefore, the results must be handled with caution.

The recycling rates assumed when determining the ecological effects at the macrolevel may be a subject of discussion. The rates are determined by a whole range of parameters, many of which are difficult to estimate (e.g. the general economic development and the developments in the plastics sector). The rates assumed for the calculations are considered ambitious, but feasible. Developments which are expected to increase the potential of recycling in the long term have not been taken into account (see also [45]). Examples in this context could be design for recycling in cars which will return as end-of-life vehicles (unless they are exported) and an increased market share of plastics which have specific advantages for recycling, e.g. polyacetals [46] or polyphenylene sulphide [47]. It is also probable that new applications will be found for mixed plastics recycling.

Cost data are only available on the recycling of plastics waste from the private sector and small consumers where a specifically high share of logistics costs is found. The amount of information on the development of costs in the future is very limited. For these reasons it is not possible to translate the findings on cost-effectiveness to other areas of plastics use. Nor is it possible to derive least-cost strategies for recycling and energy recovery. These, and related topics will have to be tackled in future research.

In spite of the limitations listed, the following findings are considered to be robust:

- In general, recycling and advanced waste-to-energy facilities clearly contribute to the goals of saving energy and curbing carbon dioxide emissions (relative to the average of current waste incineration in Germany). The only exception is mechanical recycling (BTP) where non-polymers are substituted: here the savings can be negative, but this is not necessarily the case (see Fig. 2).
- In current plastics waste management, there is large scope for improvement both in environmental and in economic terms (see Figs. 6 and 7; see Figs. 3–5).
- As far as energy saving and CO_2 abatement are concerned, recycling should be given preference over energy recovery in an average municipal waste incineration plant in Germany in the mid-1990s.
- Among those recycling technologies that are applicable for bulk waste plastics streams, mechanical recycling generally yields a high environmental benefit. However, a distinction must be made between mechanical recycling which results in products where virgin polymers are substituted and other applications which are usually manufactured from wood or concrete. In the first case the ecological advantages are among the highest of all processes studied — and there is only little uncertainty about this result; in the second case, however, the result depends to a very large extent on the specific situation.
- To ensure that as many high quality products as possible are manufactured by mechanical recycling, the effort to segregate plastics waste streams which are as pure and as uncontaminated as possible should be continued (e.g. from building waste). The same strategy should be followed in order to exploit the saving potential of BTM recycling to the highest possible degree.
- BTF recycling is clearly preferable to an average waste incinerator in Germany in the mid-1990s.
- Modern waste-to-energy facilities show clear advantages over average incineration facilities. They even exceed BTF recycling (see Fig. 2).

Consequently, this assessment of the net effects for energy consumption and CO_2 emissions does not support a general recommendation of energy recovery as is sometimes put forward in the discussions on plastics waste management. There is no doubt that incineration is advantageous in terms of environmental cost effectiveness (see Figs. 4 and 5). But only in the case of a high technological standard of incineration, with energy recovery, and with yields which are clearly better than the current average in Germany, incineration becomes competitive in terms of energy saving and CO_2 abatement (see Fig. 2). The diversity of plastics materials and the higher entropy of plastics use, i.e. the widespread use in lightweight applications, makes it much more difficult for plastics manufacturers to follow the same strategy as other virgin material producers (e.g. steel or aluminium) where recycling has become part and parcel of the product portfolio. This supports the positive attitude virgin plastics manufacturers have towards incineration.

Together with energy efficiency measures, innovations in products and the use of renewables, recycling is generally considered to be one of the key elements of sustainable development. Plastics consumption is likely to increase in the future. In contrast to other materials, especially steel, aluminium and paper, where recycling is well established, little experience is available for plastics.

The current state of plastics recycling still suffers from major drawbacks from the economic and ecological points of view. Firstly, it is still very expensive. And mainly for this reason large amounts of post-consumer plastics have to date been wasted by being deposited in landfills. As an additional problem, mechanical recycling has led to low-value products in the past which are difficult to market and the ecological benefits of which are sometimes dubious.

It is interesting to observe that DS, being the protagonist of plastics recycling in Germany, has tackled both the economic and the ecological aspect of plastics recycling [21]. Not only is the DS about to cut costs by boosting competition among recyclers; it has also become a strategic goal to correct the imbalance between supply and demand by creating high-value applications for plastics recyclates which, as this paper indicates, will very probably have a positive impact on the ecological evaluation.

The conclusions of this article are subject to changes in technologies and practices. It is very likely that the costs will decline over time as a result of R&D activities, learning processes and automation in the plastics recycling business. Life-cycle analyses, including further environmental indicators, should be performed to assess the potential of new options and to evaluate various waste management policies.

Such investigations will help to make the right choices in closing the cycles. They will also make the reasoning of the industries involved more understandable for the general public, and false expectations could thus be avoided. This is a precondition for the straightforward development and implementation of sound strategies to achieve more sustainable societies in the next century.

References

[1] Europa Chemie 29/97; Anonymous. Der Markt für Recycling-Kunststoffe wächst langsam. Europa-Chemie 29/97, 1997, p. 20.

[2] Consultic Marketing & Industrieberatung. Statistik zum Kunststoffrecycling (various years). Großostheim, 1994–1996.

[3] Müller R. Europäer für den 'Grünen Punkt'. VDI-Nachrichten (Verein Deutscher Ingenieure), 3.1.1997.

[4] von Geldern, W. Wege aus dem Wohstandsmüll. v. Hase und Köhler, Mainz 1993.

[5] Kuntze U. Plastics Recycling in Europe — Regulation, actors approaches for innovation. Report to the Center for Exploitation of Science and Technology (CEST), London, as a contribution to the

ESTO Recycling Project. Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe, March 1999.
[6] BMU (Bundesumweltministerium) German Ministry of Environment. Mit dem Entwurf eines umweltpolitischen Schwerpunktprogrammes neue Etappe in der Umweltpolitik eingeleitet — Merkel: Fuer eine Umweltpolitik mit Augenmaß. Press release. Bonn, 28.4.1998.
[7] Umweltbundesamt. Daten zur Umwelt — Der Zustand der Umwelt in Deutschland. Berlin: Erich Schmidt Verlag, 1997.
[8] Siebenlist J. Leicht ist attraktiv im Substitutions-Karussell. VDI-Nachrichten (Verein deutscher Ingenieure), 17.5.1996.
[9] Staudt E, Interthal J, Kunhenn H, Schroll M. Die Verpackungsverordnung als mißglückter Operationalisierungsversuch von Kreislaufwirtschaft. Institut für angewandte Innovationsforschung (IAI). Bochum: Ruhr-University Bochum, Paper no. 159, 1996.
[10] Deutsche Gesellschaft für Kunststoff-Recycling mbH (DKR). Mengenstromnachweis. Various press releases, various years.
[11] Deutsche Gesellschaft für Kunststoff-Recycling mbH (DKR). Geschäftsbericht 1997. Cologne: April 1998.
[12] Reh L, Büssing W. Global cycle of basic materials – a growing challenge, In: Proceedings of the conference R'99 (Recovery, recycling, Re-integration) in Geneva, 1999 (Volume II). St. Gallen, Switzerland: Published by EMPA, 1999.
[13] Heyde M, Kremer M. Recycling and recovery of plastics from packagings in domestic waste — LCA-type analysis of different strategies. Fraunhofer Institut für Verfahrenstechnik und Verpackung (IVV), Freising, vol. 5. LCA Documents, Ecomed publishers, 1999.
[14] VKE (Verband Kunststofferzeugende Industrie). Kunststoffe kann man wiederverwerten — Rohstofflich, werkstofflich, energetisch. Frankfurt/M., ca. 1996.
[15] Ayres RU, Ayres LW. Industrial Ecology — Towards closing the materials cycle. Cheltenham (UK)/Brookfield (US): Edward Elgar Publishing, 1996.
[16] Rose B. Papp–Paletten tragen Tonnengewichte. VDI-Nachrichten (Verein deutscher Ingenieure), 24.7.1998, p. 13.
[17] Pürschel C, Hartleitner B, Kreibe S, Rommel W. Maßnahmen zur Kostensenkung für die Lizenznehmer der DSD AG. Bayrisches Institut für Abfallforschung (BIfA), Augsburg, June 1998.
[18] Duales System Deutschland (DS). Der Grüne Punkt: Geschäftsbericht 1997. Cologne: May 1998.
[19] Duales System Deutschland (DS). Green dot cuts costs without cutting environmental protection — About DM one billion less by the year 2002 — European co-operation in the field of recycling. Press information. Cologne: February 5, 1998.
[20] VDI Kunststoff-Recycling unter Kostendruck — Grüner Punkt: Wiederverwerter erhalten geringere Zuschüsse. VDI-Nachrichten, 31.7.1998, p. 6.
[21] Vollrath K. Recycling von Verpackungen — Nach den Mengen jetzt die Kosten im Visier. Recycling Magazin 17/1998, pp. 17–19.
[22] Schierenbeck H, et al. Grundzüge der Betriebswirtschaftslehre (Vol. I). Oldenburg/Munich: 1996.
[23] Abell DF, Hammond JS. Cost dynamics: Scale and experience effects. In: Strategic Planning: Problems and Analytical Approaches. Englewood Cliffs, NJ: Prentice-Hall, 1979.
[24] Neij L. Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. Energy Policy 1997;23(13):1099–107.
[25] Mattsson, N. Internalizing technological development in energy systems models. Diss. Chalmers University of Technology, Göteburg, 1997
[26] Grübler A, Nakicenovic N, Victor DG. Dynamics of energy technology and global change. Energy Policy 1999;27:247–80.
[27] Campbell CJ, Laherrère JH. The end of cheap oil — Global production of conventional oil will begin to decline sooner than most people think, probably within 10 years, Sci. Am. March 1998:78–83.
[28] Chem Systems. Reduction of plastics wastes — Business impacts in Western Europe. London: Chem Systems, 1991.
[29] Sofres Conseil/TNO. Potential for post-user plastic waste recycling. Prepared for APME (Association of Plastics Manufacturers in Europe), 1998.

[30] Hutterer H, Pilz H. Kosten-Nutzen-Analyse der Kunststoffverwertung. Volkswirtschaftliche Bedeutung der stofflichen Verwertung von Kunststoffabfaellen in Oesterreich unter Einschluß oekologischer Effekte. Study prepared by GUA (Gesellschaft fuer umweltfreundliche Abfallbehandlung GmbH) for the Austrian Federal Environment Agency. Vienna: 1998.
[31] Schlotter U. Werkstoffliche Verwertung von Kunststoffen aus Altfahrzeugen — Möglichkeiten und Grenzen. Kunststoffe 8/96. Munich: Carl Hanser Verlag, 1996. pp. 1084–1087.
[32] APME (Association of Plastics Manufacturers in Europe)/VKE (Verband Kunststofferzeugende Industrie). Feedstock recycling of electrical and electronic plastics waste. Technical paper, Brussels/Frankfurt, November 1997.
[33] Brandrup J. Ökologie und Ökonomie der Kunststoffverwertung. Paper presented on the Expert Workshop 'Energetische Verwertung von Kunststoffen', Oberhausen, June 1998.
[34] Angerer G, Marscheider-Weidemann F. Behinderung der Verwertung durch die Normung. Project 'Perspektiven der werkstofflichen Verwertung von Sekundärkunststoffen der DKR'. Karlsruhe: Fraunhofer Institute for Systems and Innovation Research (ISI), August 1998.
[35] Siebenlist J. Leichtbau mit Kunststoffen ist ein absoultes Muß. VDI-Nachrichten (Verein deutscher Ingenieure), 3.4.1998. p. 22.
[36] Europa Chemie 35-36/97. Anonymous. PET-Recycling, In: Europa bereits 80 000 Jahrestonnen. Europa-Chemie 35-36/97, 1997. p. 19.
[37] De Groote P, Godard P. Mixed plastics compatibilisation. Study prepared by the Université Catholique de Louvain for the Association of Plastics Manufacturers in Europe (APME).
[38] Patel M, Jochem E, Radgen P, Worrell E. Plastics streams in Germany — an analysis of production, consumption and waste generation. Resour Conserv Recycl 1998;24:191–215.
[39] VCI (Verband der Chemischen Industrie). Responsible Care — Daten der chemischen Industrie zur Sicherheit, Gesundheit, Umweltschutz. Bericht 1997, Frankfurt, 1997.
[40] IFEU (Institut für Energie- und Umweltforschung Heidelberg). Homepage Profile and first results of a project conducted by IFEU for the Baden-Württemberg Waste Consultancy Agency (Baden-Württembergische Abfallberatungsagentur, ABAG). http://www.ifeu.de/ab_okol.htm (11.1.1999).
[41] Staeck F. Zement befeuert den Zank — Die umstrittene Mitverbrennung von Abfällen in der Industrie soll forciert werden. Entsorga-Magazin 1998;10:46–9.
[42] Müllmagazin. Bündnis 90/Die Grünen lehnen die Verbrennung von Trockenstabilat in Zementwerken ab. Müllmagazin 1998;1:5.
[43] Mark FE, Caluori A. Fuel substitution for cement kilns through source separated plastics packaging waste — The effects on metal content in clinker and on emissions. Association of Plastics manufacturers in Europe (APME), 1998.
[44] Patel M, Jochem E, Marscheider-Weidemann F, Radgen P, Thienen V. N. C—STREAMS — Estimation of material, energy and CO_2 flows for model systems in the context of non-energy use, from a life cycle perspective – Status and scenarios, vol. I: Estimates for the total system (in German). Karlsruhe, Germany: Fraunhofer Institute for Systems and Innovation Research (ISI), October 1999.
[45] Hornbogen E. Kreislauf der Werkstoffe. Mat.-wiss., u. Werkstofftech. 26, pp. 573–593. VCH Verlagsgesellschaft, 1995.
[46] Chemical engineering. The future for 'high-value' recycling of acrylics gets a boost. January 1998. p. 29.
[47] Brück M. Recycling von Polyphenylensulfid. Kunststoffe 1998;88(1):76–8.
[48] Sofres Conseil. Information system on plastic waste management in Western Europe — European Overview, 1995 and 1996 data. Prepared for APME (Association of Plastics Manufacturers in Europe). Paris: 1997.
[49] Patel M. Gross energy requirements (GER) and gross CO_2 emissions for products of the organic chemical industry (forthcoming).